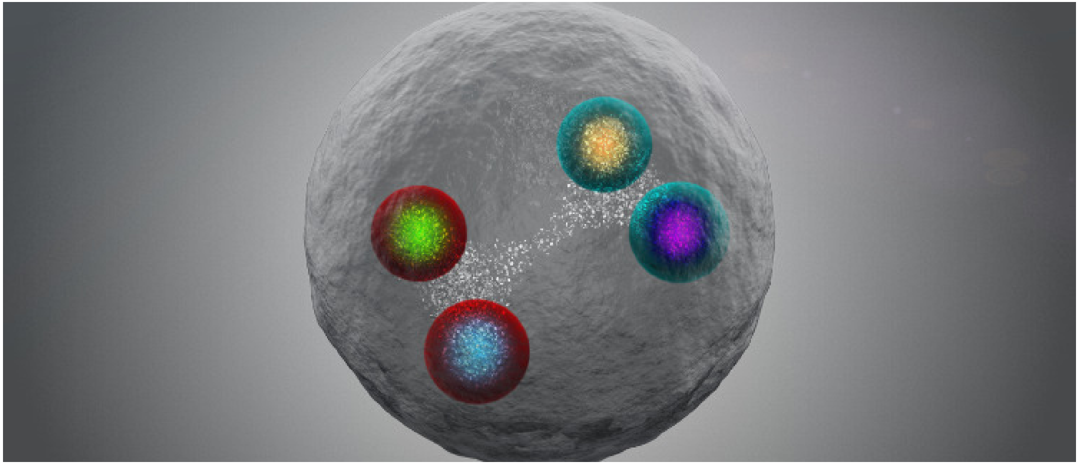
Physics of Fundamental Interactions and Particles



Particle Physics Theory: Flavour beyond the Standard Model

Prof. Andreas Crivellin

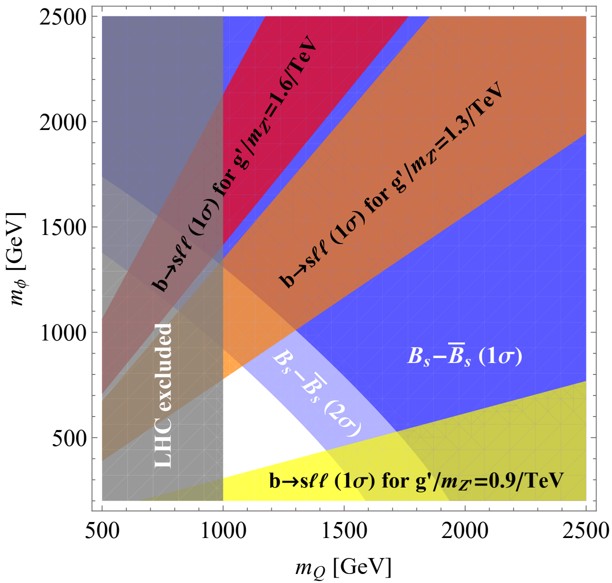
The Standard Model (SM) of particle physics describes the fundamental constituents and interactions of Nature. Matter consists of quarks and leptons (fermions) which interact via the exchange of force particles (gauge bosons). The SM has been tested to a very good accuracy, both in high-energy searches at the Large Hadron Collider (LHC) at CERN and in low energy precision experiments. However, it is well known that it cannot be the ultimate theory of nature since it fails to explain observations like Dark Matter, Dark Energy, neutrino masses or the presence of more matter than anti-matter in the Universe. The goal of our research is to construct and study models of physics beyond the SM.

https://www.psi.ch/en/ltp-crivellin

Hints for New Sources of CP- and Lepton Flavour Universality Violation

One of the predictions of the SM is that quarks and leptons appear in three generations (or families), called flavours, which only differ in their couplings to the Higgs boson, leading to different masses for particles of different flavour. The only source of flavour violation in the SM is the Cabibbo-Kobayashi-Maskawa (CKM) matrix and all SM gauge interactions treat leptons in the same way; i.e. they respect lepton flavour universality. However, several experiments found hints for deviations from lepton flavour universality, in particular in the decay of heavy B mesons (bound states involving a bottom quark).

These experimental results caused considerable interest within the theoretical community and various models for explaining them were proposed, including particles called leptoquarks (LQs). These hypothetical particles couple directly



Allowed regions in parameter space, showing that a combined explanation of the anomalies is possible.

quarks to leptons, unlike any particle in the SM. We examined the effects of LQ model in complementary observables [1]. In addition, there exist significant discrepancies between different ways of determining elements of the aforementioned CKM matrix. In particular, the CKM element determined from nuclear beta decay does not agree with the one from kaon decays. Here, we pointed out that this tension can also be explained in terms of lepton flavour universality violating physics beyond the SM as well, since beta decays involve only electrons while the best data from kaon decays is related to muons [2]. Furthermore, we investigated combined explanations of this anomaly together with the ones observed in B meson decays [3,4].

Highlighted Publications:

1. Leptoquarks in oblique corrections and Higgs signal strength: status and prospects,
   A. Crivellin, D. Müller and F. Saturnino, JHEP **11** (2020), 094 [arXiv:2006.10758 [hep-ph]]
2. β-Decays as Sensitive Probes of Lepton Flavor Universality,
   A. Crivellin and M. Hoferichter, Phys. Rev. Lett. **125** (2020) no.11, 111801
3. Explaining $b \to s\ell^+\ell^-$ and the Cabibbo Angle Anomaly with a Vector Triplet,
   B. Capdevila *et al.*, Phys. Rev. D **103** (2021), 015032
4. Combined Explanation of the $Z \to b\bar{b}$ Forward-Backward Asymmetry, the Cabibbo Angle Anomaly, $\tau \to \mu\nu\nu$ and $b \to s\ell^+\ell^-$ Data,
   A. Crivellin *et al.*, [arXiv:2010.14504 [hep-ph]]

Particle Physics Theory: Beyond the Standard Model

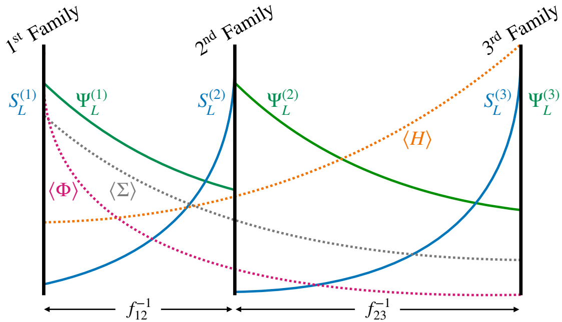
Prof. Gino Isidori

The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This Theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining cosmological phenomena such as dark matter and dark energy. It also leaves unanswered basic questions, such as why we observe three almost identical replicas of quarks and leptons, which differ only in their mass. Finally, it gives rise to conceptual problems when extrapolated to very high energies, where quantum effects in gravitational interactions become relevant. The goal of our research activity is to formulate extensions of this Theory that can solve its open problems, identifying way to test the new hypotheses about fundamental interactions in future experiments.

https://www.physik.uzh.ch/g/isidori

Flavour Anomalies and the origin of Flavour

One of the key predictions of the Standard Model (SM) is that quarks and leptons do appear in three replicas (denoted generations, or flavours) that behave exactly in the same manner under the known microscopic forces and differ only in their mass. Surprisingly enough, a series of precision measurements performed recently by the LHCb experiment at CERN seem to challenge this prediction. The theoretical investigation of these surprising results (denoted *flavour anomalies*) has been the main research activity of our group in the last four years. This research comprises four main directions: 1) the improvement of the SM predictions relevant to perform such precision studies; 2) the investigation of the consistency of the anomalous results with other data, using generic effective-theory approaches; 3) the construction of complete extensions of the SM able to describe the new data in terms of new particles and new symmetry principles; 4) the analysis of the predictions of these new interactions in view of future ex-



Schematic representation of the field profiles along the compact extra space-time dimension in the model proposed to explain the origin of the fermion hierarchies, neutrino masses, and the recent flavour anomalies.

periments. In the past year we worked mainly along the first and third direction. On the one hand, we improved the treatment of radiative corrections on rare decays within the SM. On the other hand, we developed an ambitious extension of the SM that addresses the flavour anomalies and, at the same time, provides a natural explanation for the smallness of neutrino masses. This model is based on the hypothesis of an extra compact space-time dimension. What we denote as *flavour* is nothing but a notable position along this extra dimension: the position where the geometry has a discontinuity (topological defect) and a given generation of fermion is localized. This model predicts a series of interesting phenomena, among which an anarchic spectrum on neutrinos, with average mass around 0.1 eV. It also predicts the existence of a new heavy particle called leptoquark, with mass of several TeV, which we identified in our previous studies as the best candidate to explain the flavour anomalies.

Highlighted Publications:

1. Flavour symmetries in the SMEFT,
   D. Faroughy, G. Isidori, F. Wilsch, K. Yamamoto,
   JHEP **08** (2020) 166, arXiv:2005.05366
2. Stability of the Higgs Sector in a Flavor-Inspired Multi-Scale Model,
   L. Allwicher, G. Isidori, A. E. Thomsen,
   JHEP **01** (2021) 191, arXiv:2011.01946
3. Flavor Non-universal Pati-Salam Unification and Neutrino Masses,
   J. Fuentes-Martin, G. Isidori, J. Pages, B. Stefanek,
   arXiv:2012.10492, submitted to Phys. Let. B

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

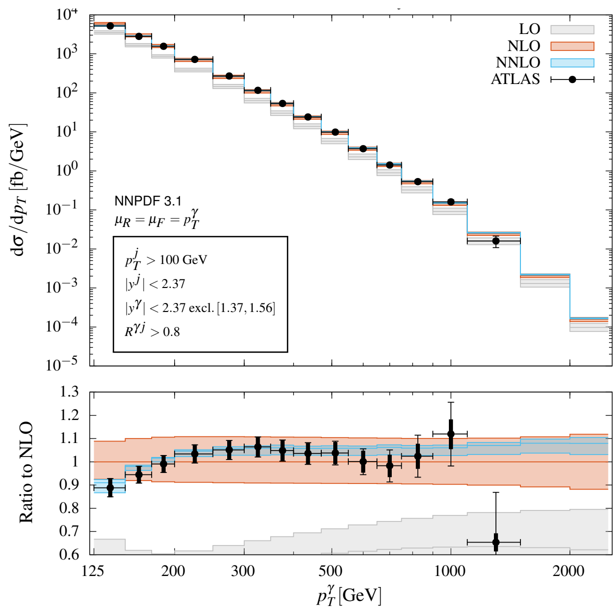
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and help to unravel the underlying mathematical structures. We implement our results into numerical parton-level event generator programs, which are flexible tools that allow to take proper account of the details of experimental measurements, enabling precision theory to be directly confronted with the data.

https://www.physik.uzh.ch/g/gehrmann

Precise theory predictions for isolated photons at the LHC

Photon production at large transverse momenta is a classical hadron collider observable. The underlying parton-level process is photon radiation off a quark produced in quark-gluon scattering, thereby offering high sensitivity to the gluon distribution in the proton. Its interpretation is however more involved than it appears at first sight. Highly energetic final state photons can also be produced as radiation in an ordinary jet production event or in the course of hadronization. To suppress these secondary contributions, an isolation procedure is applied in the experimental reconstruction of photon and photon+jet final states. This isolation procedure needs to accommodate the finite experimental resolution and must respect theory requirements on its infrared safety. It is typically accomplished by allowing only a limited amount of hadronic energy in a fixed-size cone around the photon direction.

Correspondingly, the theoretical description of isolated photon production processes must account for the isolation procedure applied in the experimental measurement. In our recent calculation of next-to-next-to-leading order (NNLO) QCD corrections to isolated photon, photon-plus-jet and di-photon final states, we employed the hybrid isolation prescription which combines the fixed cone isolation of the experimental measurement



Transverse momentum distribution of the photon in photon-plus-jet events, at LO, NLO and NNLO, compared to ATLAS 13 TeV data.

with a smaller inner cone with dynamical energy threshold that ensures infrared safety. Our calculation uses the antenna subtraction method to handle real radiation contributions and is implemented in the NNLOJET parton-level event generator framework.

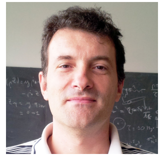
The next-to-leading order (NLO) corrections to isolated photon observables are often observed to be of comparable size to the leading-order predictions, thereby initially casting doubt on the convergence of perturbative series. With our newly derived NNLO corrections, we observe a stabilization of the predictions: the NNLO effects are typically below 10%, they lie within the uncertainty band of the previously known lower-order results. Most importantly, the NNLO corrections yield substantial improvements in the description of shapes of kinematical distributions, as illustrated in the figure. The residual uncertainty of the predictions at NNLO is typically below 5%, matching the quality of the LHC precision data.

Our newly derived NNLO corrections will enable precision studies with isolated photons, for example in determinations of the gluon distribution or in data-driven background estimates for rare processes in extreme kinematical regions.

Highlighted Publications:

1. Isolated photon and photon+jet production at NNLO QCD accuracy, X.Chen, T. Gehrmann, N. Glover, M. Höfer, A. Huss, JHEP **04** (2020) 166
2. Scale and isolation sensitivity of diphoton distributions at the LHC, T. Gehrmann, N. Glover, A. Huss, J. Whitehead, JHEP **01** (2021) 108

Particle Physics Theory: Standard Model and Higgs Physics at Colliders



Prof. Massimiliano Grazzini

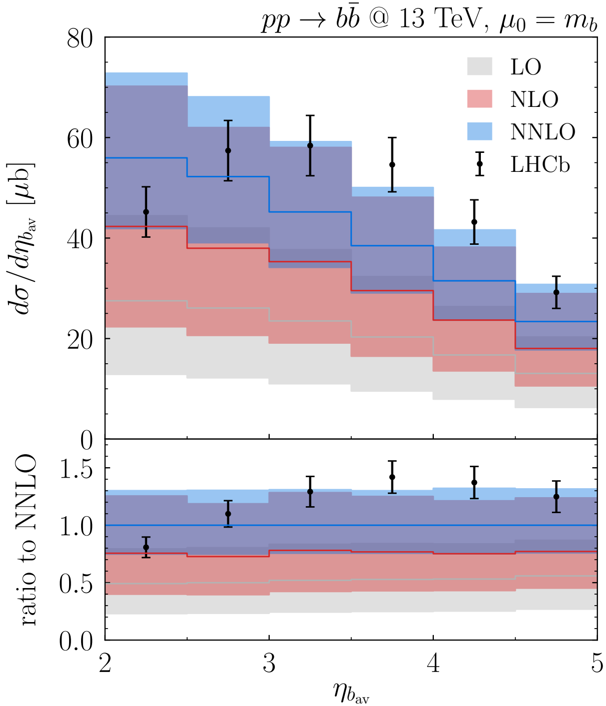
Our research activity is focused on the phenomenology of particle physics at high-energy colliders. We perform accurate theoretical calculations for benchmark processes at the Large Hadron Collider and we make their results fully available to the community. We strive to develop flexible numerical tools that can be used to perform these calculations with the specific selection cuts used in the experimental analyses. These tools can be exploited to carry out detailed comparisons with the data. Our projects span over a wide range of processes from vector-boson pair production to heavy-quark production, to Higgs boson studies within and beyond the Standard Model.

https://www.physik.uzh.ch/g/grazzini

Precise predictions for bottom quark production

The production of bottom quarks has been extensively studied at hadron colliders. Early measurements were carried out at the CERN S$p\bar{p}$S, and, later, at the Tevatron and at the LHC. From the theory viewpoint, heavy-quark production at hadron colliders is one of the most classic tests of perturbative Quantum Chromo Dynamics (QCD). The cross section to produce a pair of heavy quarks with mass m_Q is computable as a power series expansion in the QCD coupling $\alpha_S(\mu_R)$, where the renormalisation scale μ_R has to be chosen of the order of m_Q. In the case of the bottom quark the relatively low mass, $m_b \sim 4-5$ GeV, leads to a slow convergence of the perturbative expansion and, therefore, to large theoretical uncertainties. Up to very recently, the theoretical status for bottom-quark production was limited to the next-to-leading order (NLO) in perturbative QCD, with the inclusion of resummation effects at large transverse momenta.

We have completed a new computation of the bottom-quark production cross section that includes perturbative QCD corrections at next-to-next-to-leading order (NNLO). The calculation is obtained by combining tree level and one-



Pseudorapidity distribution for beauty production at the LHC for the scale choice $\mu_0 = m_b$, for centre of mass energy of 13 TeV. The theoretical predictions are compared with data from LHCb.

loop scattering amplitudes generated with OpenLoops, an automated tool also developed in Zurich, with two-loop amplitudes that are available in numerical form. The various contributions are separately divergent, and a method is required to handle and cancel infrared singularities appearing at intermediate stages of the computation. We have used the same method successfully applied by our group to the calculation of top-quark production. By using advanced numerical techniques to carry out the phase space integrations, we have assembled all the above ingredients to compute the NNLO cross section. The inclusion of NNLO corrections suggests a (slow) convergence of the perturbative series, with a significant reduction of perturbative uncertainties. We have presented several results for differential distributions for bottom quarks at the Tevatron and the LHC and compared them with available data. The inclusion of NNLO corrections generally improves the agreement with the data. More detailed data-theory comparisons will require the resummation of the logarithmically enhanced contribution at large transverse momenta and the inclusion of fragmentation effects.

1. Bottom-quark production at hadron colliders: fully differential predictions in NNLO QCD,
   S. Catani *et al.*, arXiv:2010.11906
2. Top-quark pair hadroproduction at NNLO: differential predictions with the MSbar mass,
   S. Catani *et al.*, arXiv:2005.00557

Particle Physics Theory: Automated Simulations for high-energy colliders

Prof. Stefano Pozzorini

Our research deals with the development of automated methods for the simulation of scattering processes in quantum-field theory. The OpenLoops algorithm, developed in our group, is one of the most widely used programs for the calculation of scattering amplitudes at the LHC. This tool is applicable to arbitrary collider processes up to high particle multiplicity and can account for the full spectrum of first-order quantum effects induced by strong and electroweak interactions.
Currently, new automated methods for second-order quantum effects are under development. Our phenomenological interests include topics like the strong and electroweak interactions of heavy particles at the TeV scale, or theoretical challenges related to the extraction of rare Higgs-boson and dark-matter signals in background-dominated environments.

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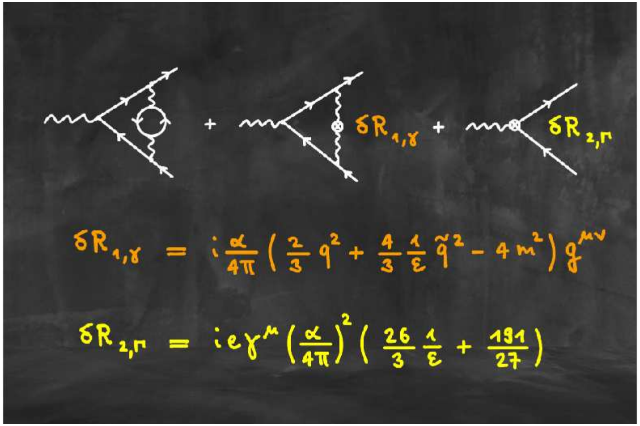
Rational terms of scattering amplitudes at two loops

Recently we did an important step forward towards the extension of the OpenLoops algorithm from first-order to second-order quantum corrections. Such corrections involve the exchange of virtual quanta with one or two unconstrained momenta, which gives rise to so-called one- and two-loop integrals. Due to the presence of ultraviolet singularities, loop integrals are typically evaluated in $D = 4 - \varepsilon$ space-time dimensions, where ε is as infinitesimally small parameter. In this way the singularities assume the form of $1/\varepsilon$ poles and can be canceled through the so-called renormalisation procedure. Finally, physical predictions are obtained by setting $\varepsilon \to 0$. In this limit, the interplay of $1/\varepsilon$ poles with infinitesimally small terms of order ε gives rise to subtle contributions, which are known as rational terms and play an important role for the automation of loop calculations.



Example of Feynman diagrams describing second-order quantum corrections to the interaction of photons (wavy lines) with electrons and positrons (solid lines). Thanks to the technique of [1][2], two-loop diagrams (left) can be computed using numerical tools in $D = 4$ dimensions, while missing contributions in $D = 4 - \varepsilon$ dimensions are reconstructed by means of one-loop (orange) and two-loop (yellow) rational counterterms. This approach is applicable to any scattering process.

So far automated algorithms exist only at one loop. In this case the most powerful approach turned out to be the combination of numerical algorithms in $D = 4$ dimensions together with special techniques for the reconstruction of the missing rational terms. Recently, as a basis for automated two-loop algorithms, we have developed a fully-fledged theoretical framework for rational terms at two loops [1],[2].

In this approach, the standard procedure for the subtraction of ultraviolet singularities is supplemented by rational counterterms, which represent universal corrections to the Feynman rules that control the fundamental interactions of elementary particles and their propagation in the vacuum. Such rational counterterms reconstruct all missing rational parts when calculations are carried out in $D = 4$ dimensions. Rational counterterms can be computed for any theory using the algorithms presented in [1],[2] and, once available, they can be applied to any scattering process. Explicit results for all two-loop rational counterterms in quantum electrodynamics and quantum chromodynamics have been presented in [1],[2], and the determination of rational counterterms for the full Standard Model of Particle Physics is within reach. These results provide an important building block for a new generation of automated algorithms for precision calculations at high-energy colliders.

Highlighted Publications:

1. Rational Terms of UV Origin at Two Loops, S. Pozzorini, H. Zhang and M. F. Zoller, JHEP **05** (2020), 077
2. Two-Loop Rational Terms in Yang-Mills Theories, J. N. Lang, S. Pozzorini, H. Zhang and M. F. Zoller, JHEP **10** (2020), 016

High-intensity low-energy particle physics

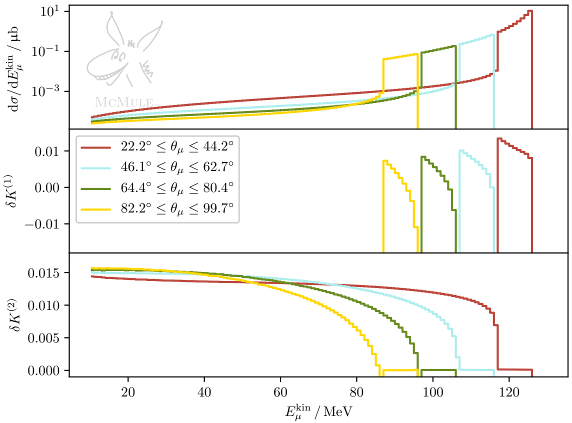
Prof. Adrian Signer

Particle physics at low energy but high intensity provides an alternative road towards a better understanding of the fundamental constituents of matter and their interactions. Using the world's most intense muon beam at the Paul Scherrer Institut (PSI) allows to look for tiny differences to the Standard Model or for extremely rare decays. Our group provides theory support for such experiments by computing higher-order corrections in Quantum Electrodynamics (QED) to scattering and decay processes and by systematically analysing the impact of experimental bounds on scenarios of physics beyond the Standard Model. These calculations are also adapted to experiments performed at other facilities with lepton beams.
https://www.physik.uzh.ch/g/signer

Elastic lepton-proton scattering

Our group has set up McMule (Monte Carlo for MUons and other LEptons), a generic framework for higher-order QED calculations of scattering and decay processes involving leptons. This framework properly treats infrared singularities when combining loop amplitudes and allows to obtain fully differential cross sections at any order in QED perturbation theory with massive fermions. The long-term goal is to provide a library of relevant processes with sufficient precision, typically at next-to-next-to leading order (NNLO) in the perturbative expansion. The code is public and the current version is available at `https://gitlab.com/mule-tools/mcmule`.

After the implementation of several processes at next-to-leading order (NLO), recently we have implemented the dominant NNLO QED corrections for elastic muon-electron and electron-proton (or muon-proton) scattering, namely to corrections due to emission off the electron line. In QED it is important to keep the fermion masses at their physi-



Differential cross section $d\sigma/dE_\mu^{kin}$ for the MUSE experiment with incoming muons of momentum 210 MeV, at NNLO with relative NLO and NNLO corrections $\delta K^{(1)}$ and $\delta K^{(2)}$. Results are shown separately for different bands of the scattering angle θ_μ.

cal value, rather than setting them to zero. This allows to compute contributions with large mass logarithms, which often produce the dominant part of the corrections in QED. This is in contrast to similar calculations in the context of Quantum Chromodynamics, where observables are typically more inclusive such that these logarithms cancel.

Very precise theoretical calculations are required for muon-electron scattering in connection with the proposed MUonE experiment which aims at an alternative determination of the leading hadronic contribution to the running of the electromagnetic coupling. Our group is contributing to this effort within the MUonE Theory Initiative and a theory summary based on a Workstop/Thinkstart event at UZH has been published. Our results for the dominant NNLO corrections have been validated by an independent computation of the Pavia group.

The MUSE experiment will measure lepton-proton scattering with $\mu^\pm$ and $e^\pm$ at PSI in the coming years. Measuring with muons and electrons of both charges in the same experimental set up will provide further insights to the proton radius puzzle and two-photon exchange contributions. We have adapted our muon-electron scattering calculation for this case and provide the most precise QED corrections to this process. As a next step, two-photon exchange contributions and radiative corrections from the proton line will be included as well.

Highlighted Publications:

1. Theory for muon-electron scattering @ 10 ppm: A report of the MUonE theory initiative, P. Banerjee *et al.*, Eur. Phys. J. C **80** (2020) no.6, 591, arXiv:2004.13663
2. QED at NNLO with McMule, P. Banerjee *et al.*, SciPost Phys. **9**, 027 (2020), arXiv:2007.01654

CMS Experiment

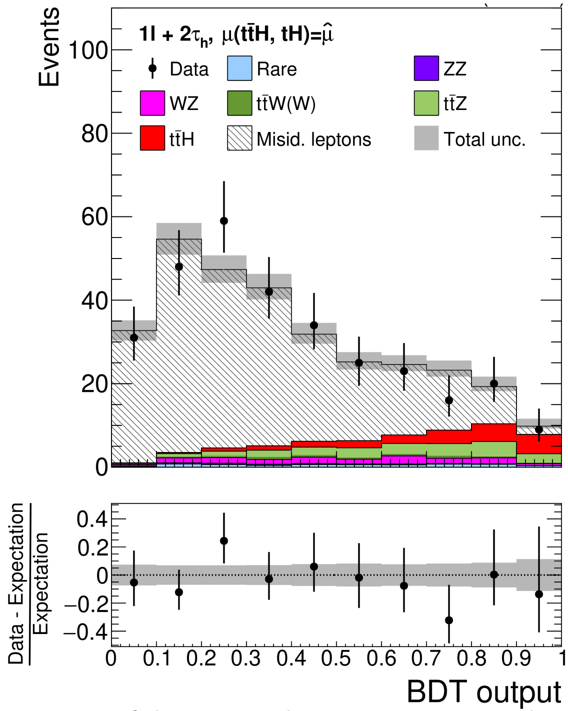
Prof. Lea Caminada, Prof. Florencia Canelli, Prof. Ben Kilminster

The CMS (Compact Muon Solenoid) experiment at CERN measures properties of the fundamental particles and their interactions, and can uncover new forces and particles. CMS surrounds one of the interaction points at the Large Hadron Collider (LHC), which produces an energy density comparable to that of the universe one ten billionth of a second after it started. Detectors are used to determine the energy and direction of emerging particles. By reconstructing these particles, the particles and their interactions can be deciphered. In 2012, CMS discovered the Higgs boson, thus proving how particles acquire mass. During Run 2 of the LHC, CMS collected a record dataset of 150 fb^{-1}, allowing more precise measurements and searches for new physics. CMS is also preparing for Run 3 in 2022, and building new detectors needed for the high-luminosity run of the LHC envisioned to start in 2027.

https://www.physik.uzh.ch/r/cms

The CMS groups at UZH are strong in data analysis, focusing on the fundamental mysteries in particle physics. We are studying the Higgs boson, and also using it as a probe to look for new forces and particles. We undergo measurements of the heaviest fundamental particle known, the top quark, which is as heavy as a gold atom, and study its interactions with other particles. In 2020, we have continued our studies of the simultaneous production of a pair of top quarks with a Higgs boson in final states with multiple leptons [1] shown in Figure 1. We have created a method to classify quark and gluon jets and reduce pileup which would be crucial in the next runs of the LHC [2] and developed anomaly detection algorithms based on advanced machine learning techniques with the goal of improving our indirect searches for new physics [3] .

The LHC is the highest energy collider in the world, which allows us to search for new heavy particles that represent hitherto unknown forces. By using a new method that simultaneously searches for combinations of particles



Measurement of the Higgs production in association with a top quark pair [1].

that would lead to mass resonances from three particles, we achieve the best sensitivity yet for dijet searches for new particles such as Gravitons and additional copies of weak force carriers [4], such as the Z′.

We have also developed a new algorithm for identifying low-momentum tau leptons that will allow CMS to measure B hadron decays to tau leptons as compared to other charged leptons [5]. This will allow us to be competitive with LHCb in the search for lepton flavor universality violation, and search for indirect evidence of leptoquarks that couple more strongly to third-generation particles. Complementary to this, we are directly searching for TeV-scale third-generation leptoquarks in their decays to high momentum particles.

Highlighted Publications:

1. Measurement of the Higgs boson production rate in association with top quarks in final states ..., CMS Collab., arXiv:2011.03652, subm. to EPJC
2. ABCNet: an attention-based method for particle tagging,
   V. Mikuni, F. Canelli, Eur. Phys. J. Plus **135**, 463 (2020)
3. Unsupervised clustering for collider physics,
   V, Mikuni, F. Canelli, arXiv:2010.07106, subm. to PRD
4. A multi-dimensional search for new heavy resonances decaying to boosted WW, WZ or ZZ ..., CMS Collab., arXiv:1906.05977, Eur. Phys. J. C **80** (2020) 237
5. Performance of the low-p_T tau identification algorithm, CMS Collab., CERN-CMS-DP-2020-039

More publications at: https://www.physik.uzh.ch/r/cms

Collider detector development

Prof. Lea Caminada, Prof. Florencia Canelli, Prof. Ben Kilminster



The CMS detector includes a silicon pixel detector as the innermost part of the tracking system. The pixel detector provides 3-dimensional space points in the region closest to the interaction point that allow for high-precision tracking of charged particles and vertex reconstruction. This enables the measurement and search for particles that decay to b quarks and tau leptons, such as the Higgs boson, the top quark, and leptoquarks. Our groups are major contributors to the CMS pixel detector project. We helped build and operate the current pixel detector and are involved in the design and prototyping of a new, improved version with more tracking layers, less material, and higher data rates to be installed in 2026. Furthermore, we are developing and testing new pixel detector concepts for high-luminosity LHC (HL-LHC), future accelerators and other applications.

https://www.physik.uzh.ch/r/cms

The current CMS pixel detector has 124 million readout channels and is capable of making 40 million measurements per second. The pixel detector has been installed in 2017 and collected collision data corresponding to an integrated luminosity of more than 150 fb^{-1} during Run 2 [1]. During the shutdown of the accelerator that is presently ongoing (2019-2022) the innermost layer of the barrel pixel detector is being replaced in order to maintain efficient and robust tracking in CMS during Run 3. The new innermost layer has been built at PSI and is fitted with the rest of the detector at CERN. We are contributing to the integration and the testing of the pixel detector as well as its re-installation into CMS and the commissioning in view of the next data-taking period (Figure 1).

CMS will collect more than 20 times the current data set during the period of 2027 to 2038 (called high-luminosity LHC). The UZH group will construct in Zurich an inner tracking detector for this period that will extend the tracking coverage. This Tracker Extended Pixel detector (TEPX) will be composed of a large-area disk system with more than

Half-disk electronics of the TEPX detector with 26 modules undergoing tests in a climate chamber. The CMS TEPX detector will consist of 1408 detector modules.

one billion pixels [2]. In 2020, we have produced first prototype modules and tested them integrated within the disk electronics and the pixel detector readout chain. A particular focus is on the verification and the characterization of the novel serial powering scheme. We studied detector sensor options that could dramatically reduce the cost of the detector, and measured the signal quality of detector modules in particle beams. Furthermore, we are prototyping lightweight mechanical structures and thin-walled cooling tubes to build the disk structures with minimal material.

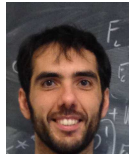
We study new types of particle detectors called LGAD, and were able to measure a timing resolution of less than 40 picoseconds ($40{\cdot}10^{-12}$ s) in our lab. In order to use these sensors in the experiment, R&D for pixelated readout electronics with fast timing measurement is needed. We are evaluating the performance of different TDC (Time-to-Digital Converter) designs that have been produced in 110 nm CMOS technology and will test their performance when processing the signals from the LGAD sensor. The long-term focus is towards a possible use of disks with timing capabilities in later upgrades of the TEPX detector. Such a technology could greatly improve the physics potential of CMS during HL-LHC.

Highlighted Publications:

1. The CMS Phase-1 Pixel Detector Upgrade, Tracker Group of the CMS Collaboration, arXiv:2012.14304, JINST **16** P02027
2. The Phase-2 Upgrade of the CMS Tracker, CMS Collaboration, CMS-TDR-014

LHCb Experiment

Prof. Nicola Serra, PD Dr. Olaf Steinkamp



LHCb is an experiment for **precision measurements** of observables in the decays of B mesons at the Large Hadron Collider (LHC) at CERN.
We play a leading role in measurements with B meson decays and in measurements of electroweak gauge boson production, and have made important contributions to the LHCb detector. We are also involved in the preparation of a major upgrade of the detector for 2019/2020.

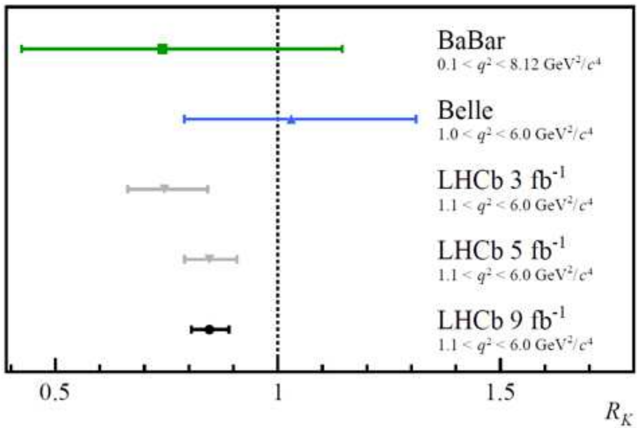
https://www.physik.uzh.ch/r/lhcb

Evidence for the violation of lepton universality in beauty quark decays

A distinctive feature of the Standard Model (SM) is the concept of lepton universality, whereby the charged leptons (electron, muon and τ-lepton) have identical interactions to the weak force. This accidental symmetry does not necessarily hold in theories beyond the SM. The LHCb group at UZH has a strong focus on testing lepton universality with beauty quark decays, whereby the behaviour of beauty quark decays into different lepton flavours is compared.

The group played a major role in a recent test of lepton universality, performed via a high precision measurement of the ratio R_K, which compares the decay probability of beauty quarks into electrons and muons. The SM prediction for R_K is unity with a theoretical uncertainty which is well below the experimental uncertainty. A deviation from unity would therefore be a indication of physics beyond the SM.

The experimental challenge lies in the fact that, while electrons and muons interact via the weak force in the same way, the small electron mass means it interacts with material much more than muons. For example, electrons radiate a significant number bremsstrahlung photons when traversing through the LHCb detector, which degrades the reconstruction efficiency and signal resolution compared to muons. The key



Comparison between R_K measurements. In addition to the new and the previous LHCb result, the measurements by the BaBar and Belle collaborations are shown [1].

to control this effect is to use the standard candle decays $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$, which are known have the same decay probability and can be used to calibrate and test electron reconstruction efficiencies. High precision tests with the J/ψ are compatible with lepton universality which provides a powerful cross-check on the experimental analysis.

The ratio R_K was measured with the full run1-run2 dataset and was found to deviate by 3.1 standard deviations (p-value $\sim$ 0.1%) from the SM prediction, constituting evidence for lepton universality violation in these decays. Interestingly, the decay probability of the electron decay is more consistent with SM predictions than the muons, suggesting that something is destructively interfering with the muonic decay and leaving the electronic decay untouched.

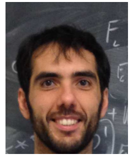
In particle physics, the gold standard for discovery is five standard deviations and so it is too early to conclude anything so far. However, this deviation agrees with a pattern of anomalies which have manifested themselves over the last decade. Fortunately the LHCb group at UZH is well placed to clarify the potential existence of new physics effects in these decays, with many related measurements upcoming soon.

Highlighted Publications:

1. All LHCb publications: lhcb.web.cern.ch/lhcb/
2. Test of lepton universality in beauty-quark decays, LHCb Collab., arXiv:2103.11769
3. Angular analysis of the $B^+ \to K^{\star +}\mu^+\mu^-$ decay, LHCb Collab., arXiv:2012.13241
4. Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$, LHCb Collab., arXiv:2103.01803

LHCb Experiment – Upgrades

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

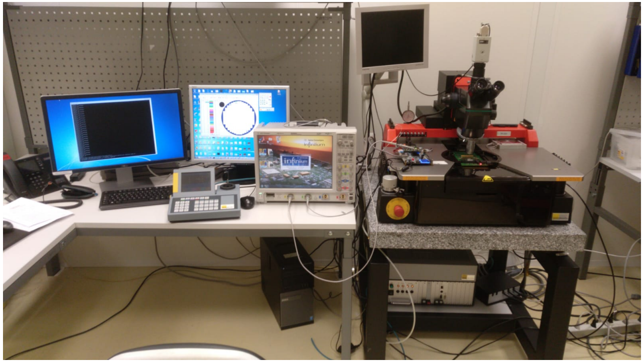


The LHCb collaboration is making use of the ongoing long shutdown of the LHC accelerator for a comprehensive upgrade of the experiment. The goal of the upgrade is to collect data at five times higher proton-proton collision rate and with better efficiency when the LHC resumes operation in 2022. Studies for a second upgrade, that would allow for another significant increase in collision rate, are gaining momentum. Our group contributes to both upgrade efforts.

https://www.physik.uzh.ch/r/lhcb

LHCb upgrade I

The contributions of our group to the LHCb detector are focussed on the so-called tracking system, a set of detectors that are employed to measure the trajectories and momenta of long-lived charged particles. The complete LHCb tracking system has to be replaced as part of the ongoing Upgrade I of the experiment. Detectors with finer granularity and better radiation hardness are needed to cope with the higher rate and density of charged particles that result from the increased proton-proton collision rate. Readout electronics have to be replaced to deal with higher trigger and data rates. Our group contributes to the development of the so-called "Upstream Tracker" (UT), a tracking station that is located in front of the LHCb spectrometer magnet and replaces the "Tracker Turicensis" which had been our main contribution to the original LHCb detector. In particular, we are responsible for quality assurance measurements of a newly developed front-end readout chip for the UT and for the development of the UT-specific firmware for the LHCb data-acquisition boards. We also contribute to the design, production and testing of various electronics boards for data taking and detector control. We plan to make significant contributions to the assembly and commissioning of the detector, which should take place at CERN in 2021.



Setup for quality assurance of front-end chips.

LHCb upgrade II

The upgraded LHCb detector has been designed to collect an integrated luminosity of about 50/fb over the next two periods of operation of the LHC. The LHCb collaboration then envisages a second comprehensive upgrade, which would allow to increase the proton-proton collision rate by another factor of five or more and collect an integrated luminosity of about 300/fb. Our group contributes to simulation studies to develop track reconstruction algorithms and understand the requirements for a tracking system for this Upgrade II. We also participate in the R&D effort to develop a novel silicon pixel detector that would allow to cover the regions of highest particle density in the tracking detectors downstream of the LHCb spectrometer magnet. The detector is based on the so-called HV-MAPS technology, Monolithic Active Pixel Sensors implemented in High-Voltage CMOS process. This technology offers a number of advantages in terms of complexity, cost and performance. It is being pioneered at the mu3e experiment at PSI, studies have also been performed for the upgrade of the ATLAS tracking system. R&D is needed to adapt this technology to the LHCb readout scheme and to demonstrate that it fulfills the requirements for Upgrade II. A first prototype sensor has been produced in 2020 and initial tests have been performed at a test beam at DESY. Further measurements at test beams and in laboratory setups, including tests of irradiated HV-MAPS detectors, as well as the submission of a second prototype are planned for 2021.

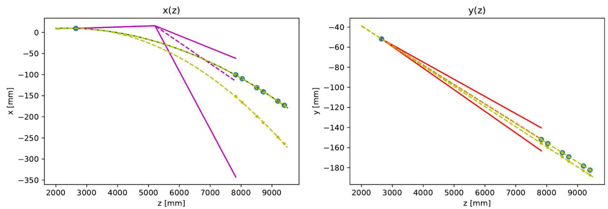


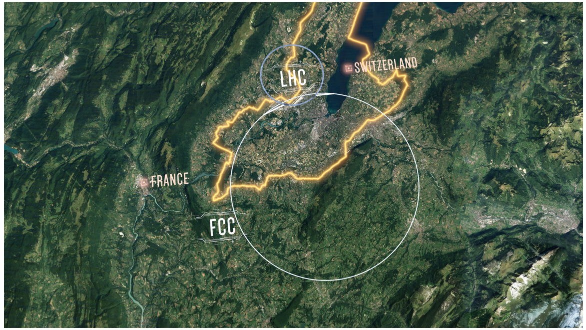
Illustration of a possible track finding algorithm in the bending plane (left) and non-bending plane (right) of the spectrometer magnet: true track (green line and dots); search window (purple resp. red lines), found track candidates (dashed yellow lines). In this example, the algorithm retrieves the correct track but also a wrong candidate.

Future Circular Collider (FCC)

Prof. Florencia Canelli

The goal of the Future Circular Collider Study (FCC) is to greatly push the energy and intensity frontiers of particle colliders and lay the foundations for a new research infrastructure that can succeed the LHC and serve the world-wide physics community for the rest of the 21st century. The FCC project envisions a staged approach, in which a new, 100-km tunnel is first used for electron-positron collisions (FCC-ee), after which the complex is upgraded to collide hadrons (FCC-hh), with the aim of reaching collision energies of 100 TeV, in the search for new physics [1].
https://www.physik.uzh.ch/r/fcc

Our group develops silicon sensor technologies for the Vertex detector with excellent precision, granularity and low mass, optimized for collisions at the FCC-ee. The measurement precision at the FCC-ee will depend on the detector technology: a vertex detector with fast read-out, low power consumption and single point spatial resolution of a few microns is



required for Higgs sector definition and particle identification for flavour physics. During 2020, our group began the development of state-of-the-art tracking detectors, together with implementing modern analysis techniques currently used at the LHC, to evaluate the physics reach of the FCC-ee.

1. Future Circular Collider - European Strategy Update Documents, M. Benedikt et al., CERN-ACC-2019-0003 (2019)

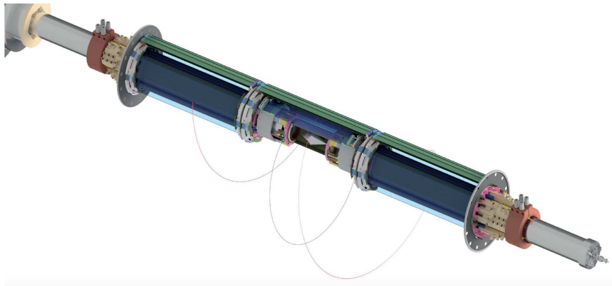


The $\mu^+ \rightarrow e^+e^-e^+$ experiment

Prof. Lea Caminada, Prof. Nicola Serra,
PD Dr. Olaf Steinkamp

The Mu3e experiment aims to search for the lepton flavour violating decay $\mu^+ \rightarrow e^+e^-e^+$. The experiment is currently finalising the design and is expected to start data taking in the next two years.

The conservation of lepton flavour, where the number of leptons in an interaction of a particular flavour is conserved, is a key symmetry in the Standard Model. Although lepton flavour violation has already been observed in neutrino oscillations, it has never been seen in charged leptons. The incredibly high intensity muon beam at PSI, Villigen offers a unique opportunity to probe lepton flavour violating decays such as $\mu^+ \rightarrow e^+e^-e^+$ and is expected to be sensitive to one $\mu^+ \rightarrow e^+e^-e^+$ decay in every 10^{16} muon decays, around 1000 times more sensitive than previous limits. We recently published the technical design report of the Mu3e experiment [1] and a first commissioning run is planned to take place this year.



Schematic of the Mu3e detector. Incoming muons are stopped in the target and decay. The resulting electrons are recorded in the pixel layers for spatial and scintillating fibre detector for time information.

1. Technical design of the phase I Mu3e experiment, K. Aandt *et. al.*, arxiv:2009.11690